INELASTIC INTERACTIONS OF PROTONS WITH PHOTOEMULSION NUCLEI AT 4·5 GeV/c*)

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In inelastic collisions of protons with photoemulsion nuclei at 4·5 GeV/c, data have been obtained on multiplicity of shower particles, energy spectrum of fast secondary protons with (2·5 ± 0·1) GeV average energy, and energy spectrum of produced charged pions with (640 ± ± 50) MeV average energy. The multiplicity, angular distributions, and energy of particles arising from splitting target-nuclei are also determined: the proton spectrum is approximated by the power dependence $E^{-\gamma}$ with $\gamma = 1·4 \pm 0·1$. The distribution of protons and π-mesons over rapidities $y = 0·5 \ln [(E + p)/(E - p)]$ have been obtained. The average multiplicity for secondary particles coincide with the predicted values given by the cascade-evaporation model.

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1. INTRODUCTION

The experimental study of relativistic nuclei interactions with nucleons and nuclei was quickly developed in the last years, and it represents a new direction in the nuclear physics facilities of accelerator technics as well as new theoretical ideas which have treated these interactions not only as the manifestation of nucleon-nucleon interactions but also as the manifestation of collective nuclear processes. The questions of limited fragmentation of interacted nuclei are also of significant interest.

In many previous papers [1–5] our collaboration has studied the interactions of relativistic nuclei of deuteron, helium, and carbon with the nuclei of photoemulsion elements at 4·5 GeV/c momentum per nucleon of accelerated nuclei. For the separation of effects which are inherent to the nucleus-nucleus interactions, the study of proton interactions with photoemulsion nuclei at the same initial momentum has a significant meaning. It also represents an independent interest from the viewpoint of revealing the nucleus-nuclei interaction mechanism at mentioned energies. The aim of this paper is to obtain the experimental data on 4·5 GeV/c proton interactions with photoemulsion nuclei and to discuss them. The analysis has been made analogically with the analysis of nucleus-nucleus interactions in [1–5]. Besides, our results are compared with the cascade-evaporation model.

2. EXPERIMENTAL PROCEDURE

In our experiment, the layers of photoemulsion BR-2 GOSNIIFOTOPROEKT with dimensions of 10 cm × 20 cm × 600 μm were irradiated in the High Energies Laboratory of JINR at Dubna by a proton beam with a momentum of 4·5 GeV/c from the JINR synchrophasotron. The density of irradiation was 2×10^4 protons/cm^2. The search of interactions was performed along the tracks of protons. We took into account the elastic interactions of $(0 + 0 + 1)$ type with relativistic track angle $\Theta < 5°$. The mean free path value obtained for inelastic interactions is $\lambda = 30{\cdot}2 \pm 0{\cdot}7$ cm.

The secondary particles were separated into s, g, and b types in accordance with ordinary photoemulsion methodical criterion:

s-relativistic particles of relative ionisation $g/g_0 < 1{\cdot}4$ (g_0 – the density of ionization along the tracks of the primary protons),

g-particles with $g/g_0 \geqq 1{\cdot}4$ and with the path in photoemulsion $R > 3000$ μm, which corresponds to the proton energy of 26 MeV,

b-particles have the path $R \leqq 3000$ μm.

The identification of b-particles in accordance with charge was performed for track dip angle less than 30° with respect to the plane of non developed emulsion taking into account the number of discontinuities in the track which depends on the remainder path. The range dependences were obtained on π-meson, proton, α particle tracks, and nucleus ^{8}Li. During the identification we took into account the dip angle of the track and its location in a photolayer [6].

Along the tracks with dip angle greater than 30° we introduced the geometrical corrections.

3. MULTIPLICITY OF SECONDARY PARTICLES

The average multiplicity values for secondary particles of different number of heavily-ionizing particles $N_h = n_g + n_b$ are given in table 1.

Table 1.

The average multiplicity values of particles.

		Number of events	$\langle n_s \rangle$	$\langle n_g \rangle$	$\langle N_b \rangle$	$\langle N_h \rangle$
all	exp.	2 576	1.63 ± 0.02	2.81 ± 0.06	3.77 ± 0.08	6.58 ± 0.12
	theory	2 307	1.75 ± 0.03	2.82 ± 0.06	3.38 ± 0.08	6.20 ± 0.13
$N_h \leqq 6$	exp.	1 602	1.68 ± 0.03	1.21 ± 0.03	1.39 ± 0.04	
	theory	1 395	1.81 ± 0.03	1.19 ± 0.04	1.06 ± 0.04	
$6 < N_h \leqq 15$	exp.	689	1.66 ± 0.04	4.40 ± 0.08	5.96 ± 0.09	
	theory	707	1.75 ± 0.05	4.46 ± 0.08	5.68 ± 0.09	
$N_h > 15$	exp.	285	1.29 ± 0.06	7.96 ± 0.15	11.80 ± 0.17	
	theory	205	1.36 ± 0.07	8.22 ± 0.19	11.23 ± 0.18	
$N_h > 6$	exp.	974	1.55 ± 0.04	5.45 ± 0.09	7.67 ± 0.12	
	theory	912	1.67 ± 0.04	5.31 ± 0.09	6.93 ± 0.11	

In the group with $N_h \leqq 6$ there are interactions with light nuclei of photoemulsion and "peripheral" interactions with heavy nuclei. The group with $N_h \geqq 7$ is formed by events which occured on heavy photoemulsion nuclei only. The results of calculations in the framework of the cascade-evaporation model are presented here [7].

We observed an agreement between the experimental and calculated values, and the accuracy of these values is approximately 10% as follows from the table.

The contribution of events with a complete disintegration of nuclei Ag, Br ($N_h \geqq 28$) is small, 0·5%. The contributions of these events are 2·2% and 3·2% if the energies of incident protons are 6·2 GeV and 22 GeV, respectively [8, 9].

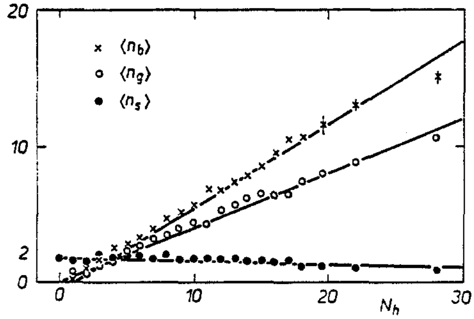


Fig. 1. The dependence of $\langle n_s \rangle$, $\langle n_g \rangle$, $\langle n_b \rangle$ on N_h.

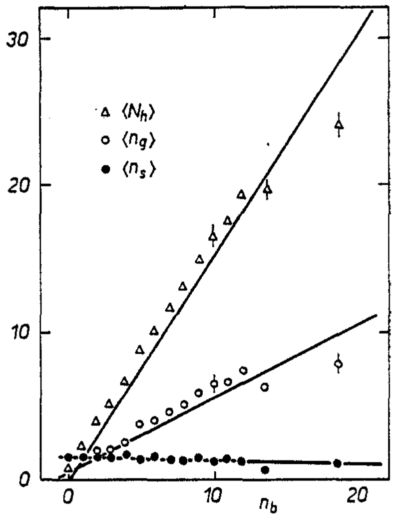


Fig. 2. The dependence of $\langle n_s \rangle$, $\langle n_g \rangle$, $\langle N_h \rangle$ on n_b.

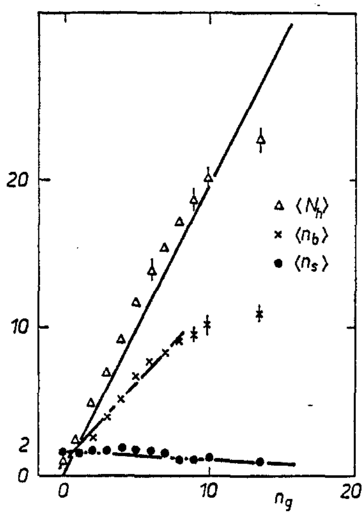


Fig. 3. The dependence of $\langle n_s \rangle$, $\langle n_b \rangle$, $\langle N_h \rangle$ on n_g (for $\langle n_b \rangle$ fit in the region of $n_g \leqq 8$).

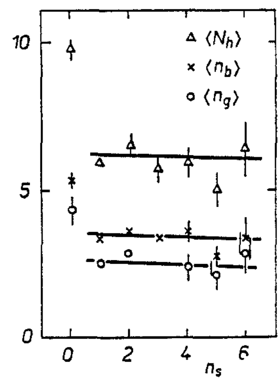


Fig. 4. The dependence of $\langle n_g \rangle$, $\langle n_b \rangle$, $\langle N_h \rangle$ on n_s (fit in the region of $n_s \geqq 1$).

Table 2.
The inclination coefficients — "K"

	$\langle n_s \rangle$	$\langle n_g \rangle$	$\langle n_b \rangle$	$\langle N_h \rangle$
n_s	—	-0.04 ± 0.04	0.01 ± 0.04	-0.03 ± 0.06
n_g	-0.06 ± 0.01	—	1.09 ± 0.02	1.97 ± 0.02
n_b	-0.03 ± 0.01	0.51 ± 0.01	—	1.52 ± 0.02
N_h	-0.02 ± 0.00	0.40 ± 0.01	0.60 ± 0.01	—

The correlations of multiplicities, $\langle n_i \rangle = f(n_j)$, and their approximations by linear dependence, $\langle n_i \rangle = a + kn_j$, are given in figures 1 to 4. The values of the inclination coefficients are given in table 2.

A weak decrease of $\langle n_s \rangle$ with the increasing number of heavily-ionizing particles attracted our attention. This indicates the absence of visible meson formation in the secondary processes as well as knocking-out the relativistic particles with the increase of impact parameter after the scattering.

One can see from figure 4 that the degree of disintegration of a target nucleus does not depend on the number of s-particles in the event, with the exception of the events with $n_s = 0$ which originate perhaps with a large probability in the interactions with the heavy nuclei of photoemulsion. This circumstance must be verified in experiments on emulsions of the different compositions.

4. ANGULAR CHARACTERISTICS OF SECONDARY PARTICLES

The values of the half angle $\frac{1}{2}\Theta_s$ and distribution of $\eta_s = -\ln \operatorname{tg} \frac{1}{2}\Theta_s$ are convenient characteristics for the s-particle analysis. For g-particles we have used $\frac{1}{2}\Theta_g$ and $\langle \cos \Theta_g \rangle$, for b-particles the value F/B – the ratio of the number of particles emitted

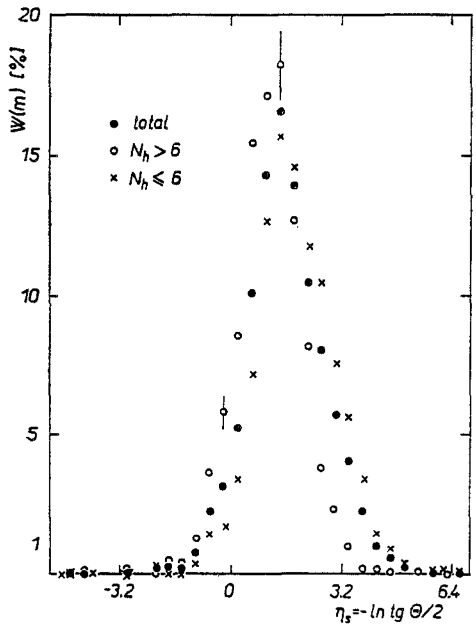


Fig. 5. The distribution of $\eta_s = -\ln \operatorname{tg}(\frac{1}{2}\theta_s)$ for different groups of events on N_h.

into the forward and backward hemispheres. The distributions of η_s are shown in figure 5, and the values of the angular characteristics for different intervals of the multiplicity N_h are given in table 3.

Table 3.
The angle characteristics.

N_h	$\leqq 6$	7—15	$\geqq 16$	$\geqq 7$	$\geqq 0$
$\frac{1}{2}\theta_s$ °	$19{\cdot}0 \begin{smallmatrix} +0{\cdot}7 \\ -0{\cdot}6 \end{smallmatrix}$	$32{\cdot}4 \begin{smallmatrix} +1{\cdot}9 \\ -1{\cdot}3 \end{smallmatrix}$	$47{\cdot}3 \begin{smallmatrix} +2{\cdot}6 \\ -1{\cdot}1 \end{smallmatrix}$	$35{\cdot}8 \begin{smallmatrix} +1{\cdot}9 \\ -1{\cdot}5 \end{smallmatrix}$	$24{\cdot}4 \begin{smallmatrix} +0{\cdot}8 \\ -0{\cdot}6 \end{smallmatrix}$
η_s	$1{\cdot}85 \pm 0{\cdot}02$	$1{\cdot}21 \pm 0{\cdot}03$	$0{\cdot}80 \pm 0{\cdot}05$	$1{\cdot}10 \pm 0{\cdot}03$	$1{\cdot}57 \pm 0{\cdot}02$
$\frac{1}{2}\theta_g$ °	$60{\cdot}6 \begin{smallmatrix} +1{\cdot}9 \\ -1{\cdot}9 \end{smallmatrix}$	$64{\cdot}5 \begin{smallmatrix} +1{\cdot}5 \\ -2{\cdot}1 \end{smallmatrix}$	$66{\cdot}5 \begin{smallmatrix} +1{\cdot}4 \\ -1{\cdot}0 \end{smallmatrix}$	$65{\cdot}3 \begin{smallmatrix} +1{\cdot}2 \\ -1{\cdot}3 \end{smallmatrix}$	$63{\cdot}8 \begin{smallmatrix} +1{\cdot}3 \\ -1{\cdot}0 \end{smallmatrix}$
$\langle \cos \theta_g \rangle$	$0{\cdot}37 \pm 0{\cdot}01$	$0{\cdot}31 \pm 0{\cdot}01$	$0{\cdot}28 \pm 0{\cdot}01$	$0{\cdot}30 \pm 0{\cdot}01$	$0{\cdot}32 \pm 0{\cdot}01$
$(F/B)_b$	$1{\cdot}29 \pm 0{\cdot}06$	$1{\cdot}31 \pm 0{\cdot}04$	$1{\cdot}23 \pm 0{\cdot}04$	$1{\cdot}27 \pm 0{\cdot}03$	$1{\cdot}27 \pm 0{\cdot}03$
$(F/B)_p$	$1{\cdot}2 \pm 0{\cdot}2$	$1{\cdot}1 \pm 0{\cdot}1$	$1{\cdot}0 \pm 0{\cdot}1$	$1{\cdot}04 \pm 0{\cdot}08$	$1{\cdot}1 \pm 0{\cdot}1$
$(F/B)_\alpha$	$2{\cdot}0 \pm 0{\cdot}4$	$1{\cdot}5 \pm 0{\cdot}3$	$1{\cdot}2 \pm 0{\cdot}2$	$1{\cdot}33 \pm 0{\cdot}15$	$1{\cdot}45 \pm 0{\cdot}14$

From this table it follows that with the increase of the disintegration degree of a nucleus — target, the angular distribution of s-particles is extended, while for the g-particles this tendency is less expressed.

The ratio F/B for protons in stars with different N_h is practically unity: some anisotropy in all the groups of events is observed for α-particles.

We note that in the angular distributions of slow protons and α-particles we did not observe statistically justified non-regularities.

5. ENERGY CHARACTERISTICS OF SECONDARY PARTICLES

The momenta of the s-particles were determined by the multiple scattering method on 354 tracks with dip angle from 5° to 10° with respect to the emulsion plane by following introduction of geometrical corrections on these restrictions.

Further we have made the separation of the measured s-particles on protons and π-mesons. The selection of s-particles is in accordance with the criterion $g/g_0 < 1{\cdot}4$, except the contribution of protons in the region of $p\beta \leqq 680$ MeV/c. The separation of particles in the region of $p\beta > 680$ MeV/c was made statistically with the consideration of pion spectrum to this boundary.

The pβ spectrum and dotted protons and pion spectrum in the region of $p\beta >$ > 680 MeV are shown in figure 6. The average energies are:

$$\langle E_\pi \rangle = (642 \pm 50)\,\text{MeV} \quad \text{and} \quad \langle E_p \rangle = (2536 \pm 120)\,\text{MeV}\,.$$

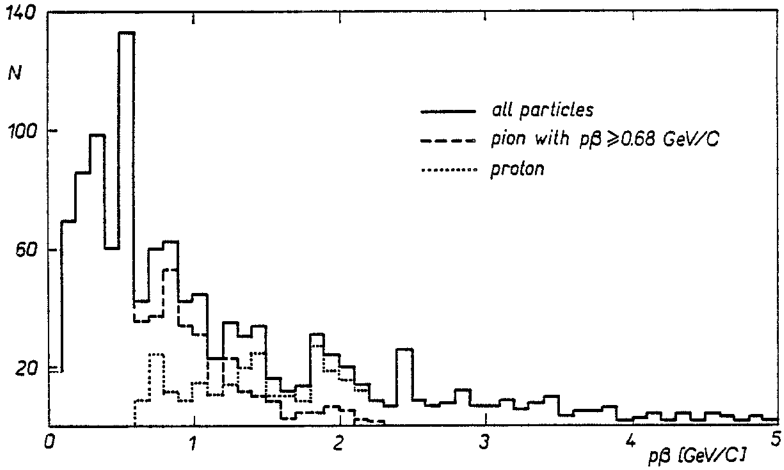


Fig. 6. The distribution of pβ for all measured s-particles and separately for protons and pions in the region of $p\beta > 680$ MeV/c.

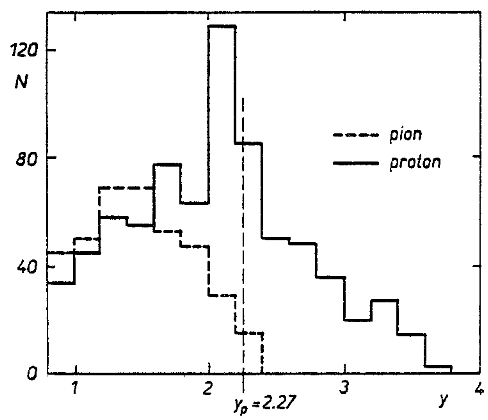


Fig. 7. The distribution of pions and protons among the s-particles rapidity $y = 0{\cdot}5 \ln[(E+p)/(E-p)]$.

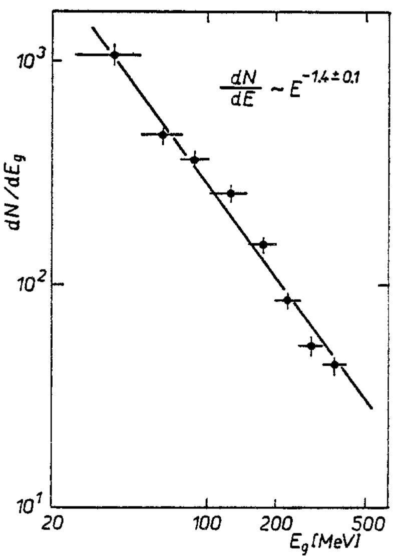
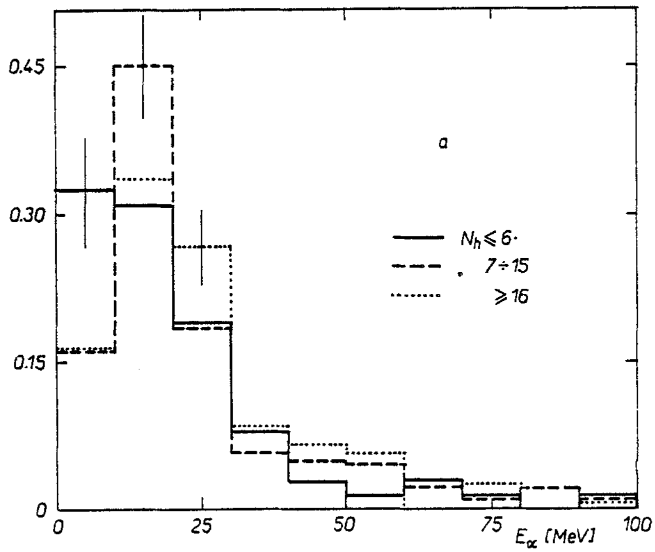


Fig. 8. Energy spectrum for g-particles.

The distributions of protons and π-mesons versus rapidity $y = 0{\cdot}5 \ln\left[(E+p)/(E-p)\right]$ are given in figure 7.

The energy of g-particles (we assume them to be protons) was determined either from the path or from the measurements of the relative ionization g/g_0. Energy spectrum of g-particles, which is shown in figure 8, can be approximated by power dependence $E^{-\gamma}$ where $\gamma = 1{\cdot}4 \pm 0{\cdot}1$. With increasing N_h some softening of the spectrum can be observed, what is in agreement with the modification of angle characteristics of g-particles.



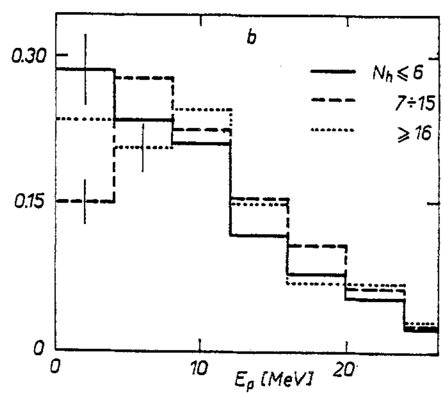


Fig. 9. Energy spectrum for slow α-particles (a) and for protons (b) in the events with different number of heavily-ionising particles N_h.

Table 4

The energy characteristics.

N_h	≦6	7–15	≧16	≧0
$\langle E_g \rangle$ MeV	122 ± 5	110 ± 4	103 ± 5	112 ± 3
$\langle E_p \rangle_b$ MeV	8·8 ± 0·4	10·4 ± 0·3	9·7 ± 0·4	9·7 ± 0·2
$\langle E_\alpha \rangle_b$ MeV	19·4 ± 1·7	23·5 ± 1·5	23·5 ± 1·3	22·6 ± 0·8
$(\alpha \mid p)_b$	0·44 ± 0·05	0·40 ± 0·04	0·55 ± 0·05	0·46 ± 0·03

The energy of b-particles was determined from the range using the dependence $E = f(R_{p,\alpha})$.

The average energy values of g and b-particles for the different groups are given in table 4. There is some growth of $\langle E_p \rangle$ and $\langle E_\alpha \rangle$ for the stars with $N_h \geqq 7$ which is caused apparently by the influence of the Coulomb barrier. By decreasing the impact parameter with heavy nuclei (by increasing N_h) the energy spectra of b-particles extend both at greater and at smaller energy sides (figure 9).

6. CONCLUSIONS

In the present paper we have studied the basic characteristics of the inelastic interactions of protons with 4·5 GeV/c momentum with the emulsion nuclei.

We have shown that there is an agreement of average multiplicities of secondary particles with the cascade-evaporation model, simultaneously for the experiment and for the groups of events with small multiplicities of h-particles. We intend to perform an analysis with the separation of interactions into the light and heavy nuclei group [4] after receiving analogical data on photoemulsion enriched by light nuclei.

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